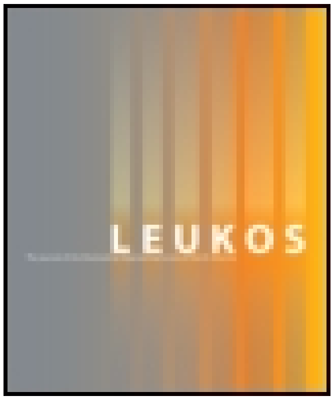

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Toward a Replacement of the CIE Color Rendering Index for White Light Sources

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ABSTRACT The CIE color rendering (fidelity) index (CRI) has remained unchanged for over four decades. Most, if not all, of its components could be updated to more state-of-the-art methods. One of the most critical components of any color rendering (fidelity) metric is the test sample selection. This article therefore addresses the importance of uniform sampling of wavelength space to avoid selective optimization—that is, taking advantage of the unequal contributions of different wavelength regions to the general color rendering score—of light source spectral power distributions. It summarizes the development of a mathematical sample set with undistorted spectral sensitivity, the HL17 set. The set is used in a recently proposed update, the CRI2012 general color rendering index. To assess the impact of the spectrally uniform sample set on color fidelity scores, the CRI2012 index values for each of a set of 139 lamps were compared with those of the CIE CRI. In addition, the impact of updating the other components was investigated. A mean and maximum absolute difference of respectively 5.9 and 21.8 index units were found between the CRI2012 and CIE CRI, although the largest part—respectively 4.03 and 19.7 index units—was shown to be the result of updating the color difference engine and the switch to the CIE 10° observer. The analysis also indicated possible past spectral selective optimization of some warm-white tri-band fluorescent sources for high luminous efficacy of radiation (LER) and (just) sufficient CIE R_a values by taking advantage of the spectral nonuniformity of the CIE reflectance set. Adopting a spectrally uniform sample set in a color rendering metric therefore has important practical implications when designing light source spectra. Finally, possible updates and further improvements of the CRI2012 are briefly mentioned.

KEYWORDS color quality, color rendering, color rendition, CRI2012, HL17, light sources, spectral power distributions, spectral sensitivity, spectral uniformity

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1. INTRODUCTION

Objects often look different depending on the light source illuminating them. For example, they often appear oversaturated under a three-band light source, whereas most halophosphate fluorescent lamps have a desaturating effect. These differences in color appearance are caused by the differences in interaction between the spectral reflectance of the object and the specific shapes—the bumps and wiggles—of the spectral power distributions (SPDs) of the light sources. *Color rendering* specifically refers to the impact of the SPD on the color appearance of objects under a test lamp relative to a defined standard source [Houser and others 2015]. Traditionally, color rendering has been evaluated using the CIE CRI [CIE 1995]. However, beginning soon after its standardization in 1974, there has been a growing body of literature and anecdotal evidence concerning its accuracy in predicting the color rendering or color quality of narrow-band or spiked spectra [Bodrogi and others 2004; CIE 2007; Sándor and Schanda 2006; Smet and others 2011; Szabó and others 2007]. This issue has become more pressing with the advent of light emitting diode (LED) light sources, because the inability to correctly predict the color rendering of lamps based on narrow band LEDs might result in unexpected lighting quality effects that could inappropriately impact their degree of acceptance. In other words, especially with current innovation in light sources, we cannot rely on the CIE CRI to be an adequately accurate gauge of color rendering. For clarity, it is helpful to point out that the CRI and the improvement CRI2012 described here are purely what could be called *fidelity metrics*. This is important to recognize, because in addition to having an accurate fidelity metric, many people would like to have additional information about the SPD of a lamp source—which would involve assessment of the desirability of various types of color distortion caused by lamp, relative to a test standard. Such aesthetic considerations are far more complex and are receiving considerable attention [Dikel and others 2014; Wei and others 2014], but they lie outside the scope of this article. Color preference metrics attempting to predict such aesthetic issues are based mainly on chroma enhancement [Davis and Ohno 2010], gamut area (expansion/contraction) [Davis and Ohno 2010; Freyssinier-Nova and Rea 2010; Hashimoto and others 2007], and memory and/or preferred colors [Smet and others 2012; Yano and Hashimoto 1998]. This article focuses on the simpler, more objective topic of *color fidelity*. More specifically, it summarizes possible updates to the different components of the CIE CRI as proposed in the CRI2012 [Smet and others 2013] and, in particular, it addresses the importance of using a spectrally undistorted sample set in the color fidelity calculation. Finally, some more recent updates to the CRI2012 calculation are discussed as well.

2. BACKGROUND: ESSENTIAL DETAILS OF THE CRI2012

The CRI2012 metric follows the outline of a typical fidelity calculation (see Fig. 1). Almost all steps, except for the first two—related to the choice of reference illuminant—have been updated to improve upon the shortcomings of the CIE CRI. What follows is a high-level overview of the basic steps required to calculate the general color rendering index $R_{a,2012}$.

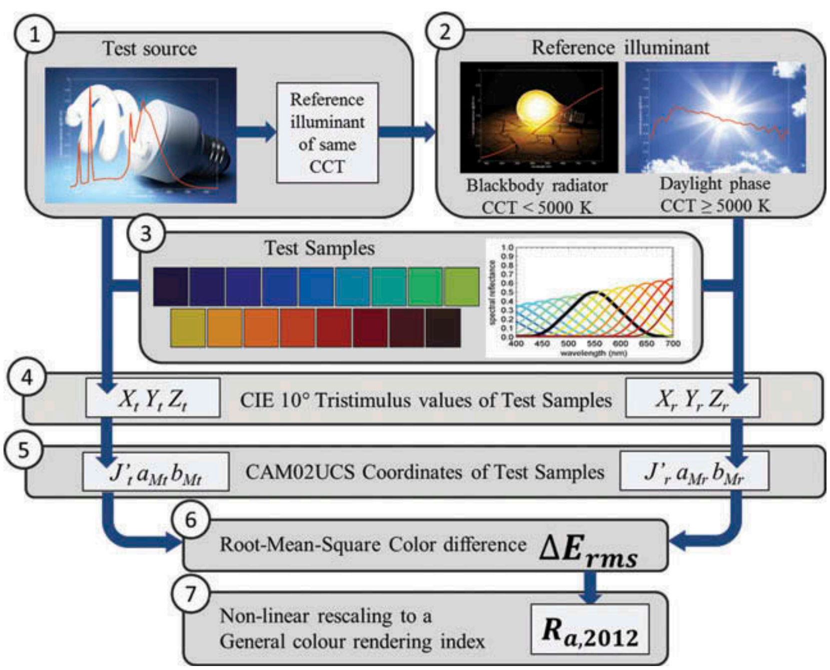

Fig. 1 **Calculation scheme of the general CRI2012 fidelity index.**

First, based on the correlated color temperature (CCT) of the test light source, a reference illuminant is calculated according to the method employed in the CIE CRI (steps 1 to 2 in Fig. 1): a blackbody radiator for CCTs smaller than 5000 K and a daylight phase for CCTs above that. The reference illuminant provides an objective measuring stick to compare the color rendering properties of the test source against. Note that the reference illuminants, which were selected because they are common and well defined, are not necessarily optimal in terms of predicting perceived naturalness, preferred appearance, or any other subjective aspect of visual color rendering.

The HL17 test samples—replacing the 14 Munsell samples of the CIE CRI and specially designed to have an undistorted spectral sensitivity (see next section)—are illuminated (mathematically) by the test source and reference illuminant: for each sample, under both the test and reference illuminant, the CIE 10° tristimulus values are calculated (steps 3 to 4 in Fig. 1). The CIE 10° observer was chosen because the 2° is known to be in error for shorter visible wavelengths, resulting in a discrepancy between visual and colorimetric matches [Csuti and Schanda 2008, 2010]. CCT is, however, still calculated using the CIE 2° standard observer [Ohno 2014].

To take into account the characteristics of the human visual system and the impact of viewing conditions, the tristimulus values are then converted to the $J'a_Mb_M$ color coordinates in the perceptually uniform CAM02-UCS space [Luo and others 2006] (step 5 in Fig. 1). The latter is the state of the art in color appearance modeling and replaces the outdated $U^*V^*W^*$ and von Kries adaptation transform in the CIE CRI.

In any fidelity metric, the color appearance of test samples under the test light source is compared to their appearance under the reference illuminant by calculating the color difference for each sample. A general measure for the fidelity is obtained by taking the root mean square (RMS) average of the individual color differences (step 6 in Fig. 1). An RMS measure is used—in contrast to the arithmetic average of the CIE CRI—to ensure the poor rendering of a few samples is well reflected in the general index.

Finally, the RMS color difference is converted to a general color rendering index, $R_{a,2012}$, using a nonlinear rescaling function to avoid negative values [Smet and others 2013]. Specific color rendering indices $R_{i,2012}$ can be calculated in a similar manner from the individual color differences. However, for hue-specific information, the CRI2012 has specified an additional set of samples, the Real210 set. The reasons for the adoption of two different sample sets are described in the next section.

3. SAMPLE SET CONSIDERATIONS

Sample set selection is undoubtedly one of the most critical and important steps in the design of a color rendering metric [David 2014]. One way to understand why is to consider one of the earliest proposed metrics to assess the color rendering properties of a light source: the test band method proposed by Bouma [1937]. The principle behind this approach is to compare the SPD of a test source directly with that of a broadband reference source—after all, color rendering specifically refers to the impact of the SPD—by dividing wavelength space in a number of bands (Fig. 2). Each band provides approximate information on the similarity of the reference and test source SPD within it.

There are, however, several problems with this approach. Which bands should be selected? How many?

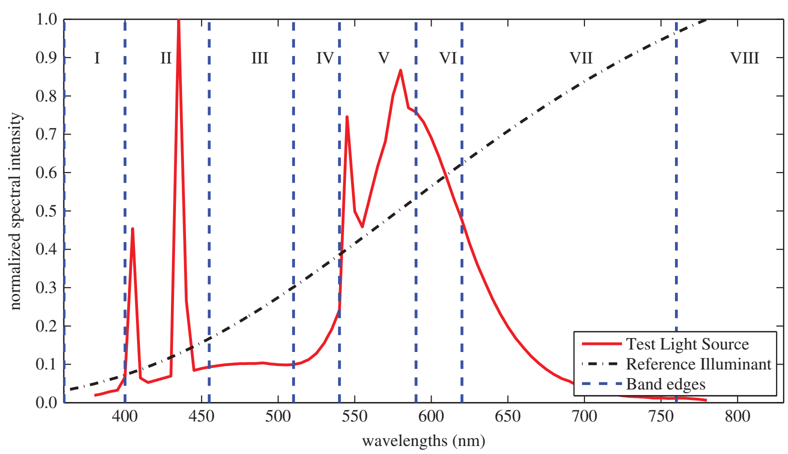

Fig. 2 **Band method approach to color rendering evaluation of a test source (solid red line) in comparison with a reference illuminant (dashed black line). The edges of the bands are drawn in a dashed blue line.**

What is the importance of each band for color rendering? What function should be used to compare the SPD of the test source and the reference illuminant? And especially, how are the differences in SPD best translated to perceptual differences in color rendering?

To solve these issues, it is helpful to consider the bands themselves to be equivalent to spectral reflectance functions that have the value 0 outside of the band and the value 1 within it. This transforms the problem from a band method to a test sample method (Fig. 3), with the corresponding "digital" spectral reflectance functions effectively sampling the wavelength space.

For each of these theoretical samples, color differences can be calculated in any chosen color space, thereby solving the issue of translating differences in SPD to perceptual differences. In the above case, each part of wavelength space is sampled only once. In other words, in a specific wavelength region, differences in the SPD of the test source with respect to that of the reference illuminant contribute only once to the overall color rendering evaluation.

Though such an approach could be undertaken, the overall desire in the lighting community is to have real reflectance samples, which could be used in a visual assessment. However, because real reflectance functions have bumps and wiggles all over wavelength space, they might sample specific wavelength regions more than others—that is, the set could have a spectrally nonuniform sensitivity, and this could be true even if their corresponding color coordinates were uniformly distributed in color space. Such nonuniformity is concerning, because it can be exploited when selectively optimizing the SPD of light sources because certain regions of wavelength space contribute more than their correct share to the color rendering score; that is, some regions are more sensitive to spectral features than others.

There are several ways to assess the (non)-uniformity of the spectra of a sample set. One approach is to consider the average of the curvature of the reflectance functions in the set [Smet and others 2013] (also see Fig. 4) or even more generally as the first-order, second-order, or even higher order moments of the reflectance functions' first and second (and higher) derivatives [David and others 2015]. Another is to sweep wavelength space with a narrow spectral feature. More specifically, one or more CIE reference illuminants are perturbed with a narrow spectral feature located at ever increasing wavelengths. The spectral sensitivity of a sample set is then defined as the average color difference error relative to the unperturbed reference illuminant as a function of the perturbation wavelength. Spectral features of different shapes (for example, sensitive to first, second, or higher derivatives) and spectral widths can be used.

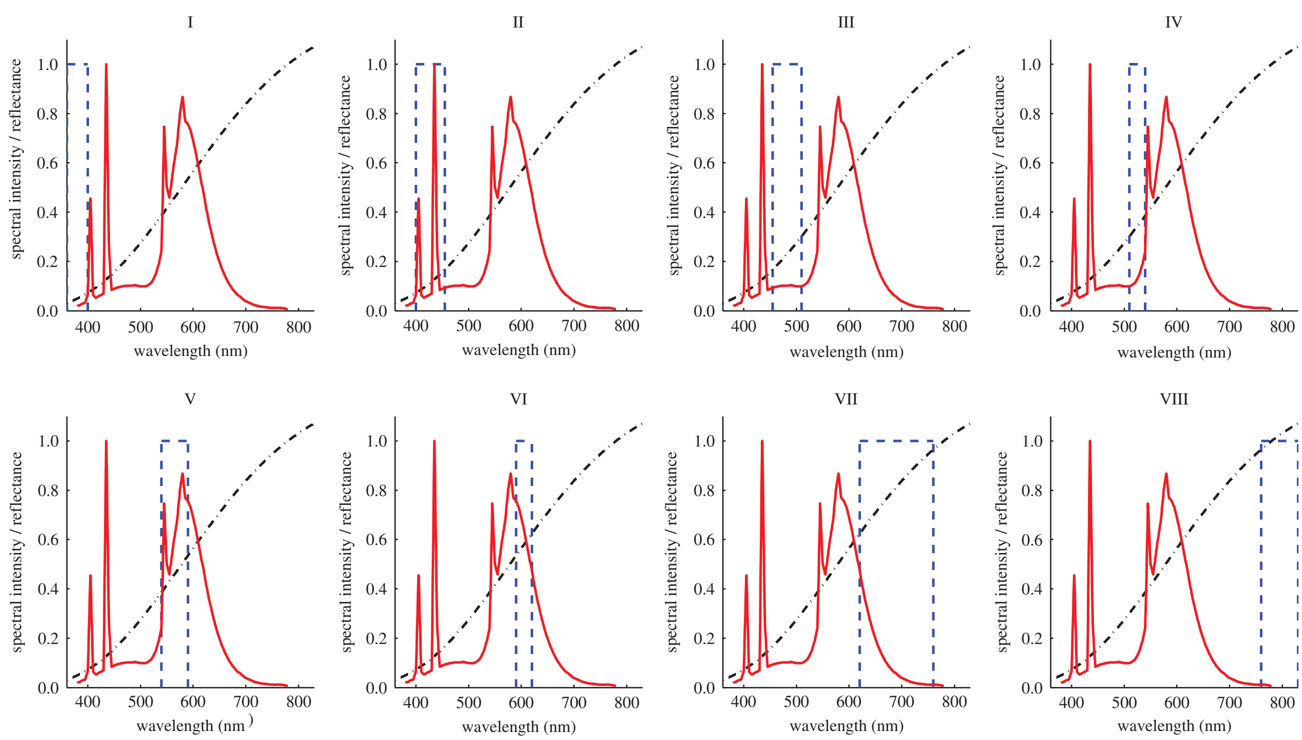

Fig. 3 **Test sample method equivalent of the band method of Fig. 2.**

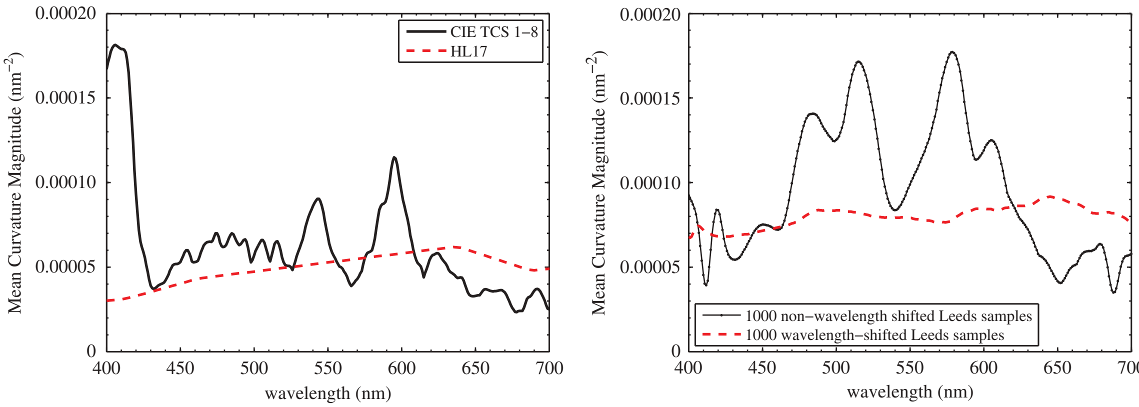

Fig. 4 **Spectral sensitivity of several spectral reflectance function sets. Left: The CIE TCS 1-8 and the HL17, both used in the calculation of a general color rendering index. Right: A set of 1000 randomly selected non-wavelength-shifted spectral reflectance functions and the 1000 wavelength-shifted spectral reflectance function set.**

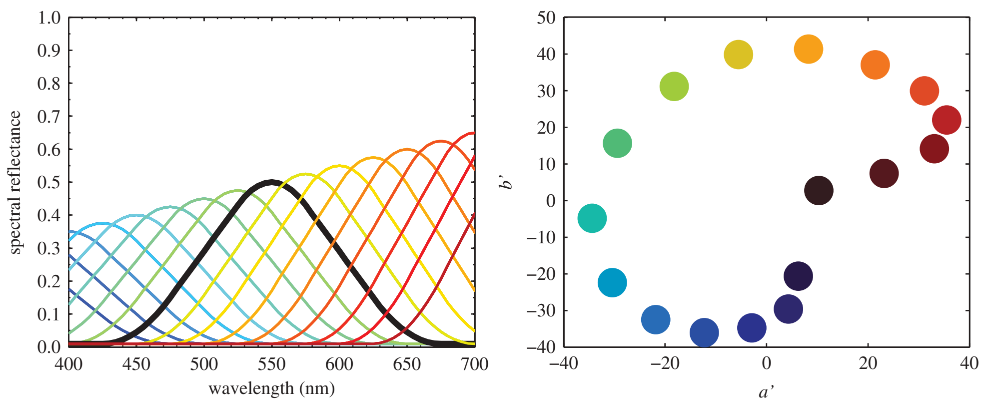

Fig. 5 **HL17 used in the calculation of the general $R_{a,2012}$ index. Left: spectral reflectance functions. Right: $a'b'$ chromaticity coordinates in the CAM02UCS space.**

The perturbation approach (second derivative sensitive shape and with spectral widths of 10 and 20 nm) was taken to derive the HL17 set (Fig. 5) used in the CRI2012 [Smet and others 2013]. Because the perturbation approach takes the inherent sensitivity of the human visual system into account through the use of a color appearance difference, ideal spectral uniformity is not characterized by a horizontal line response—it necessarily falls off at either end of the visible spectrum and has variations throughout that are reminiscent of the well-known variation in wavelength discrimination throughout the visible band. The HL17 set spectral sensitivity was therefore optimized to match that of a set of 1000 wavelength-shifted reflectance functions. In addition to matching the spectral sensitivity of the wavelength-shifted set, the HL17 was simultaneously optimized to closely match its color error predictions for a set of 53 lamp spectra and to have a high correlation between its $R_{a,2012}$ scores and the visual ratings obtained in a color fidelity experiment with over 40 sources of five different CCTs [Szabó and others 2007].

The 1000 wavelength-shifted spectra had by design a uniform spectral sensitivity. They were obtained by a wavelength shifting process—which ensures that each spectral feature (bump or wiggle) has the same probability of being located at every wavelength—of a larger set of 10,000 reflectance samples randomly selected with uniform density in $L^*a^*b^*$ from an even larger set of 100,000 real spectral reflectance functions collected at the University of Leeds [Smet and others 2013]. The spectral sensitivity—evaluated here as the mean curvature magnitude—of the HL17, the 1000 wavelength-shifted, and the eight test samples (TS1-8) used in the calculation of the CIE R_a are shown in Fig. 4.

From Fig. 4, it is clear that the 1000 wavelength-shifted and HL17 spectra are much more spectrally uniform, which, as explained earlier, is important when selectively optimizing light source SPDs. It is also clear that random selection of a large number of reflectance spectra will not remedy spectral nonuniformity. Uniform spectral sensitivity has to be built in carefully in any color rendering set.

Although the HL17 set uniformly samples wavelength space, its sampling of color space is less uniform. In addition, the number of samples (17) is too limited for many applications requiring more detailed—for example, hue-specific—information. For this reason, the CRI2012 has adopted another set, the Real210 set, which is composed of 210 spectral reflectance samples: 90 high-color-constancy and 90 low-color-constancy metameric samples, 10 artist paints, and four times five skin tone samples (Fig. 6).

The drawback of the Real210 set is that although it samples color space uniformly, it is not spectrally uniform and so cannot be used to calculate a general color rendering index.

4. COMPARING THE CRI2012 WITH THE CIE CRI

The $R_{a,2012}$ and the CIE R_a scores for 139 lamps—56 traditional fluorescent lamps (halophosphate, tri- and multiband), 15 High Pressure (HP) discharge lamps, 68 led lamps (Red-Green-Blue, Red-Green-Blue-Amber, and phosphor whites)—are plotted in Fig. 7. It is clear that there are some shifts in metric scores compared to the CIE R_a, but this is, of course, expected because the CRI2012 was designed to fix many of the problems with the CIE CRI. A mean absolute difference of 5.9 index units was found between the two CRI metrics for the set of 139 lamps. These differences, though not massive for most lamps, are also not negligible, so it is worthwhile to consider the degree to which the various changes adopted in the CRI2012 contribute to these differences. As already described, the changes in CRI 2012 fall

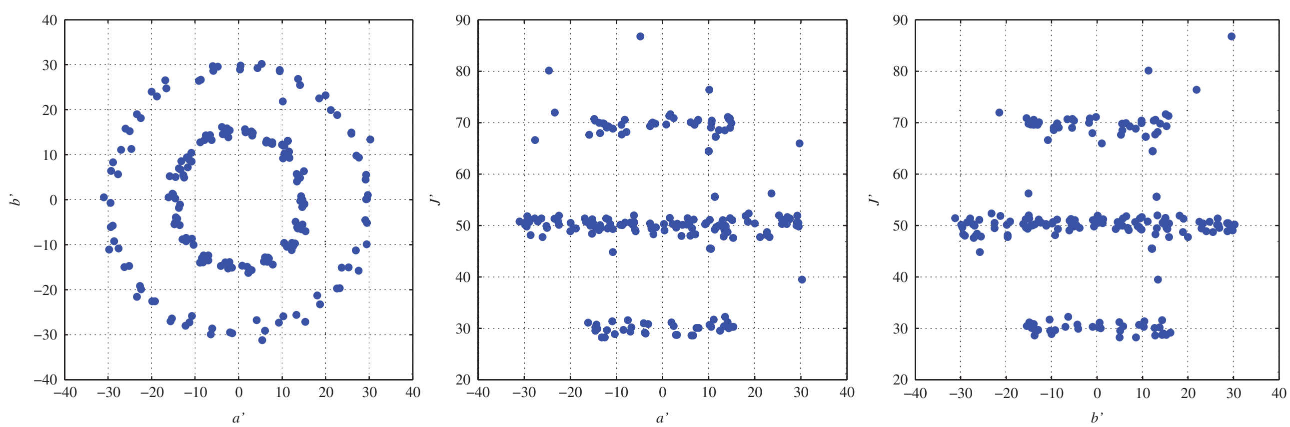

Fig. 6 Real 210 set—plotted in CAM02UCS space—for more hue-specific information.

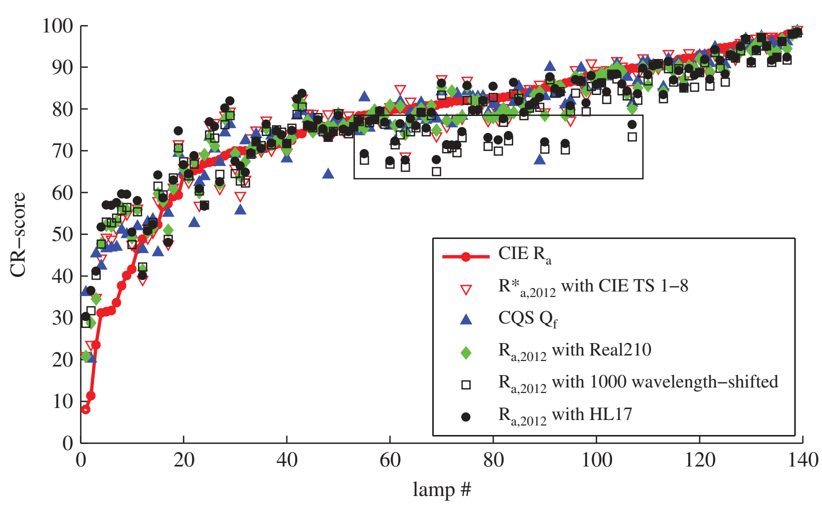

Fig. 7 Comparison of the index values of several color rendering metrics for 139 lamps.

into four categories: (1) switch from the CIE 2° standard observer to the CIE 10° observer, (2) update of the color difference engine (from using the $U^*V^*W^*$color space, the von Kries chromatic adaptation transform, and the arithmetic averaging to using the CAM02UCS color appearance space with RMS averaging), (3) use of a nonlinear (S-shaped) rescaling function instead of the simple linear function ($R_a = 100 - c \cdot \Delta E$) used in the CIE CRI, and (4) switching from the eight CIE test samples to the spectrally uniform HL17 sample set. The mean absolute differences introduced by each of these four categories are, respectively, 1.5, 3.2, 3.1, and 3.3 index units. By itself, the effect of switching the sample set is of the same magnitude as updating the color difference engine or switching to a nonlinear rescaling function. Interestingly, at 1.5 units, the effect of a change from the CIE 2° observer to a 10° observer is quite substantial. The maximum absolute differences—respectively 11.2, 17.4, 9.2, and 17.6—generally follow the same trend as those of the mean, except for perhaps the change to an S-shaped rescaling function. The latter shows a maximum absolute difference approximately half of that observed for the updates of the color difference engine and sample set, and the mean absolute differences were comparable for these three. Another way of analyzing the contribution of each of these categories is by sequentially adding them to the CRI calculation—starting from the CIE CRI—and calculating the difference relative to each preceding step. The relative contributions of each category are, respectively, 1.47, 2.56, 0.21, and 1.55 index units in the case of the mean absolute difference and 11.2, 8.5, −2.9, and 5.0 index units for the maximum absolute difference. Clearly, the combined effect of an update to a better color difference engine—using a more uniform color space—and the switch from the CIE 2° to 10° observer to resolve the inaccuracy of the CIE 2° observer at shorter wavelengths is responsible for the largest part—respectively 4.03 and 19.7 index units for the mean and maximum absolute difference—of the observed difference between the two metrics. It may also be noted that the switch from a linear rescaling function to a nonlinear one has a negligible effect (0.21 index values) on the mean differences, whereas the effect was actually positive for the maximum difference scores; that is, they actually become smaller (−2.9 index values).

In Fig. 7, the index values of the $R_{a,2012}$ scores obtained by replacing the default HL17 with other spectral reflectance sets—the CIE TCS1-8, the Real210, and the 1000 wavelength-shifted spectral reflectance functions—and the index values of the CQS Q_f (v9.0) [Davis 2011] are also plotted for comparison.

From Fig. 7 it is also clear that there are some lamps that score about 10 index units lower on the CRI2012 than on the CIE CRI (see rectangle). These lamps are mainly warm-white (CCT $\leq$ 4000 K) triband fluorescent sources for which there is anecdotal evidence that the CIE R_a value is overestimating the visually observed color rendering. A plot of these triband sources in a CIE R_a versus $R_{a,2012}$ graph (see Fig. 8) clearly shows that the drop in scores is limited to light sources that have high luminous efficacy radiation (LER) values and with CIE R_a scores between approximately 80 and 85. Coincidently, both in Europe and in the United States, norms and standards specify a minimum R_a value of 80 for general and office lighting. It seems plausible that these light sources are examples of light source SPDs that were selectively optimized for high LER and sufficient CIE R_a by taking advantage of the unequal contributions to the color rendering score of different wavelength regions in the CIE reflectance set (cfr. spectral nonuniformity). Because the CRI2012 uses a spectrally uniform reflectance set in its calculation of the general color rendering index its use has important practical implications when designing light source spectra.

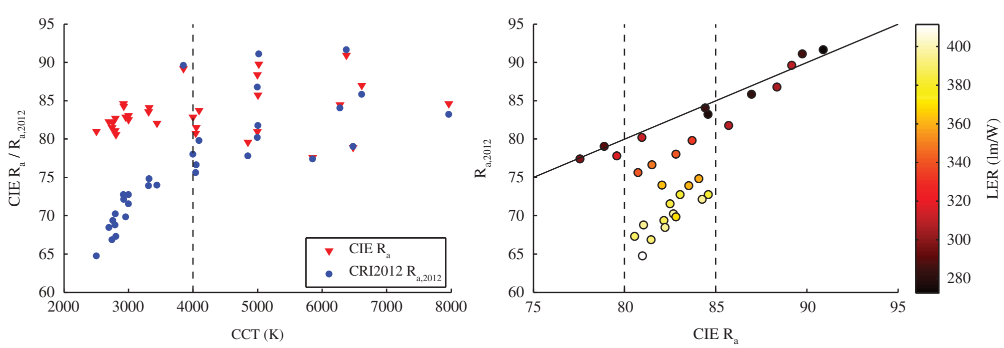

Fig. 8 **Left: $R_{a,2012}$ (circles) and CIE R_a (triangles) scores versus the CCT of a set of 31 triband fluorescent sources. Right: CIE R_a versus the $R_{a,2012}$ for the same set of light sources but color coded for LER. Note how the drop in $R_{a,2012}$ scores is limited to high LER lamps that fall within a small CIE R_a range slightly above the minimum R_a value of 80 for general and office lighting.**

5. CRI2014: REPLACING THE MATHEMATICAL HL17 WITH A REAL SET

Ideally, a single set of real spectral reflectance functions would be used for both the calculation of the general color rendering index—requiring spectral uniform sensitivity to avoid selective optimization—and the special color rendering indices for hue specific information—requiring uniform sampling of color space with a sufficiently large number of samples.

The CRI2014, which will be proposed in an upcoming publication [David and others 2015] will provide just such a set.

In addition, the possibility of updating the reference illuminant calculation is being investigated. The goal would be to avoid a discontinuity that currently exists at 5000 K—at which point the reference illuminant switches type. A better alternative could be to spread this transition into a continuous shift over a range. For example, from 4500 K to 5500 K, the reference source could be a weighted average of a Planckian radiator and a daylight phase (both having the specified CCT at each point), whereby the relative weighting smoothly transitions from entirely Planckian at 4500 K to entirely daylight phase at 5500 K. Neither of these improvements is expected to dramatically change the predictions of CRI 2012, but it is hoped that they will further improve general acceptance of a CRI fidelity metric that is free of spectral sensitivity distortion.

6. SUMMARY

After a high-level overview of the CRI2012 [Smet and others 2013] in which the major differences with the CIE CRI have been highlighted, the importance of uniform sampling of wavelength space to avoid selective optimization (that is, using the unequal contributions of different wavelength regions to the general color rendering index score) has been discussed. The work on the development of a mathematical sample set with uniform spectral sensitivity, the HL17 set, has been briefly summarized. A comparison of the CRI2012 and the CIE CRI general index scores for a set of 139 light sources showed a mean and maximum absolute difference of 5.9 and 21.8 index units. A further analysis showed that a large part of the difference in index values between the two metrics—respectively 4.03 and 19.7 units for the mean and maximum differences—is due to the combined effect of a switch in CIE observer—2° to 10°—and the update of the color difference engine. The latter involves a change from the $U^*V^*W^*$ color space and von Kries chromatic adaptation to the CAM02UCS color space and a change to an RMS average. The introduction of the nonlinear rescaling function had, respectively, a negligible and positive effect for the mean and maximum differences. Finally, the metric comparison also showed that the CRI2012 index values for warm-white triband fluorescent sources—whose visual color rendering tends to be overestimated by the CIE CRI—are substantially lower than those predicted by the CIE CRI. Interestingly, the effect—lower CRI2012 scores—is limited to SPDs with high LER and with CIE R_a values within a narrow range starting at 80. The latter happens to be the lower limit proposed by many North American and European norms and standards for color rendering suitable for general lighting and office lighting. It seems plausible that this is the result of past selective optimizing of light source spectra for high LER and a (just) sufficient CIE R_a, thereby illustrating the practical importance of the spectrally uniform reflectance set used in the CRI2012. Finally, some anticipated updates to the CRI2012 were briefly mentioned.

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